

HUMAN RESEARCH FACILITY REFREIGERATED CENTRIFUGE THERMAL ANALYSIS REPORT

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CRITICAL DESIGN REVIEW

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1 INTRODUCTION

The Refrigerated Centrifuge is a payload installed in a Human Research Facility Rack that will be flown on International Space Station. It is used to separate biological samples based on variation of density and provide refrigeration. It will be able to separate blood into its components and separate saliva from saturated cotton rolls. The Refrigerated Centrifuge is packaged in a 12 PU drawer (Fig 1.1). The Refrigerated Centrifuge will provide refrigeration to the rotor chamber from ambient to 4 C. This temperature will be displayed while in use.

It uses a vapor compression cycle for refrigeration. The refrigeration system consists of a compressor, a condenser, an evaporator and an expansion device. The rotor attached to the motor is used for spinning the samples.

The door in the front panel of the unit will provide access to the rotor chamber. The door will be closed after samples are inserted. The controls for temperature, rotor speed and time could be set.

The major heat dissipating components are the evaporator, compressor, Power Converter Supply Module (PCSM), rotor motor, lid lock solenoid and PCBs located on the evaporator. A condenser fan is provided to remove heat from the refrigeration system. This fan is located inside the unit, just ahead of the compressor. Two fans are used to provide cooling to the components inside the unit. The exhaust air passes through heat exchangers mounted in the HRF Rack directly behind the cooling fans.

The thermal analysis of the Refrigerated Centrifuge was performed to predict the temperature distribution inside the unit, to calculate touch temperature, and to determine whether condensation would be formed on the front surface. The software package ICEPAK was used to develop the Flow Model. The flow rates from fans were predicted using this model during the nominal operation of the unit. The thermal model was developed using SINDA.

The lowest temperature on the Refrigerated Centrifuge door is checked to determine whether it would cause condensation when exposed to the ISS environment ranging with a dew point from 4.4° to 15.6° C (40° to 60° F) and a relative humidity from 25 to 75%. The temperature/humidity envelope defined by these dew point and relative humidity ranges for air is shown in Figure 1-2. (LS-71000).

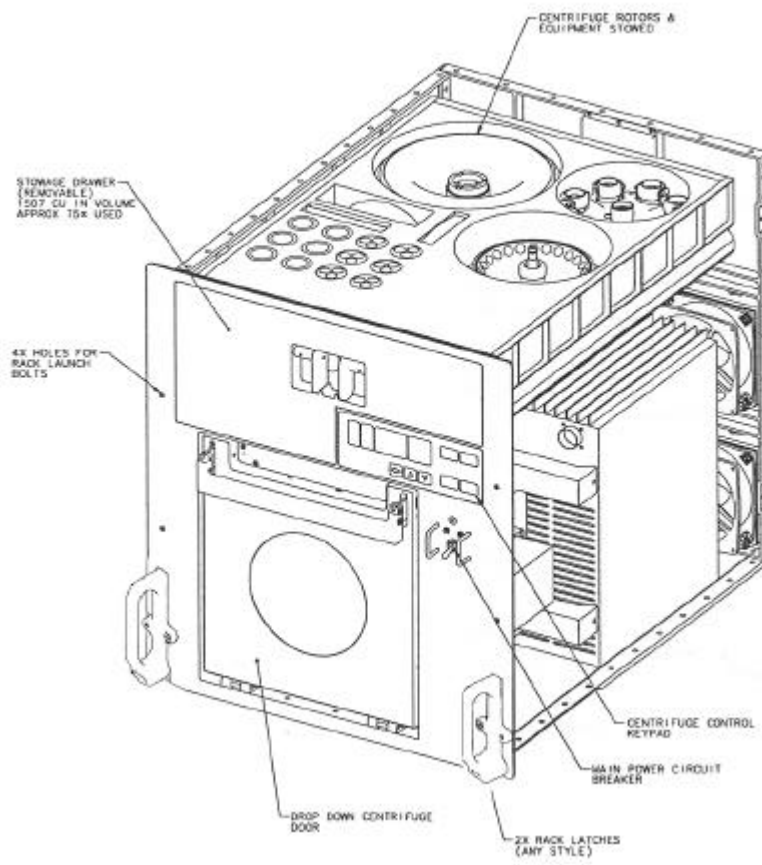


Figure 1.1 HRF Refrigerated Centrifuge

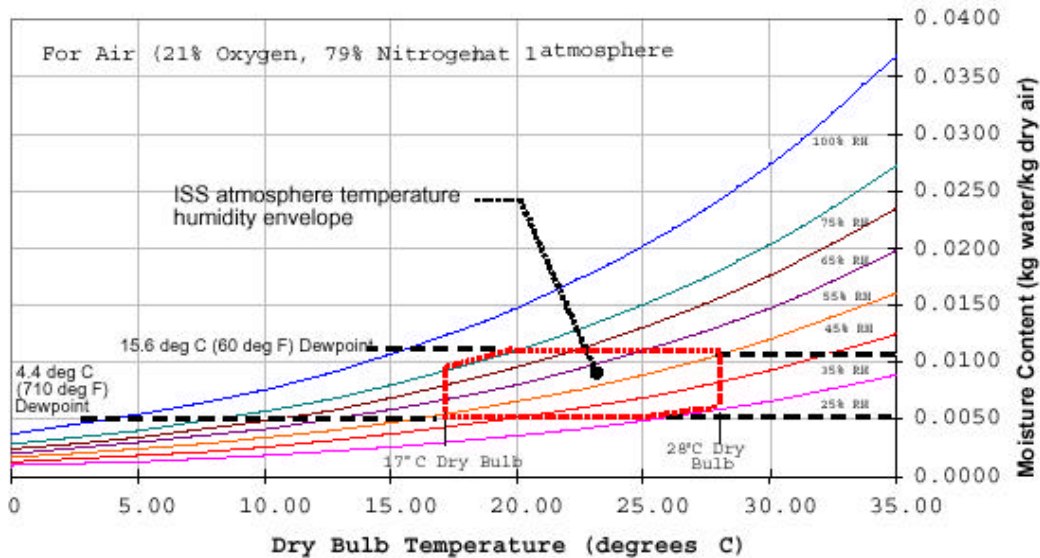


Figure 1-2. ISS Environment Temperature/Humidity Envelope

It has to be noted that the dew point limit is 15.6 C for an ambient temperature range from 20 C to 28 C.

The Refrigeration loop inside the unit goes through ON/OFF loop depending on the efficiency of the compressor. The duty cycle for the operation time of Refrigeration Centrifuge (30 minutes) is shown in Table 1-1.

Time in Minutes Showing the Duty Cycle of Refrigeration (30 Minute Operation)							
ON	7.1	2.4	2.8	2.3	2.3	2.4	2.3
OFF	1.5	1	1.5	1.5	1.4	1.5	

Table 1-1 Duty Cycle of Refrigeration

The heat loads for the nominal case during the ON/OFF refrigeration cycle are shown in Table 1-2.

Heat Dissipation in W		
Components	Ref ON	Ref OFF
Common Fan1	26.6	26.6
Common Fan2	26.6	26.6
Frequency Controller	4	0
Power Board	1.2	1.2
Cooling Board	1	1
Lid Lock Solenoid	6	6
DC/DC Converter	168	21.3
Rotor Motor	37.5	37.5
Condenser+Fan	543.1	0
Compressor	136	0
Total	950	120.2

Table 1-2 Heat Load

The following cases are considered for analysis.

Case1) Nominal operation with a cabin air temperature of 28C

Case2) Nominal operation with a cabin air temperature of 20 C
to check for condensation on door

Case3) Failure of both external cooling fans

Case4) Failure of one external cooling fan assuming the same duty cycle after fan failure

Case5) Failure of one external cooling fan assuming continuous refrigeration loop
after fan failure

2 ASSUMPTIONS

The following assumptions were made in the development of the models for the Refrigerated Centrifuge:

- Cabin air temperature is assumed to be 28 °C for Nominal Operation.
- Chamber is set at 4 °C.
- Avionics air temperature is 32 °C.
- Convection coefficient of the cabin air is assumed to be 1.14 W/m² K.
- Convection coefficients for the avionics air are assumed to be 2.34 W/m² K on the top and bottom of the drawer and 5.678 W/m² K on the back and sides of the drawer.
- Emissivity for anodized aluminum is assumed to be 0.8. Emissivity of other metal surfaces is assumed to be 0.3.
- The heat load for the Power converter Supply Module is imposed on the base plates of Heat Sink

3 MODEL DESCRIPTION

A thermal model was developed using SINDA to determine the temperature distribution of the components, air and enclosure of the unit. The flow model was developed using ICEPAK to determine the flow pattern and predict the flow rate through the unit. A brief overview of the theory and description of the models are presented in this section.

3.1 Description of ICEPAK Flow Model

In order to analyze flow and predict flow rate through the unit, the discretized Navier Stokes equations are solved. The solution is obtained in terms of velocity and pressure at the discrete points in the domain. The governing equations for incompressible flow are:

Continuity Equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Momentum Equations:

$$\begin{aligned}\rho\left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z}\right) &= -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) + X \\ \rho\left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z}\right) &= -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) + Y \\ \rho\left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z}\right) &= -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) + Z\end{aligned}$$

Where:

u, v, w = x, y and z components of velocity

X, Y, Z = x, y and z direction body forces per unit volume

p = pressure

ρ = Density

μ = Dynamic viscosity

These equations are discretized and solved using the ICEPAK software package.

A computational grid is generated after developing the model and a numerical solution is obtained at these grid points. The flow distribution inside the unit is obtained and the flow rate through the unit is computed from this solution.

The model is developed using the standard ICEPAK objects such as “plate,” “block,” “PCB,” “Vent,” “Opening” and “fan.” The flow model of the Refrigerated centrifuge is shown in Figure 3.1-1. The fan curves (Pressure Drop Vs. Mass Flow Rate) of the external cooling fans and condenser fan are shown in Figure 3.1-2 and Fig 3.1-3.

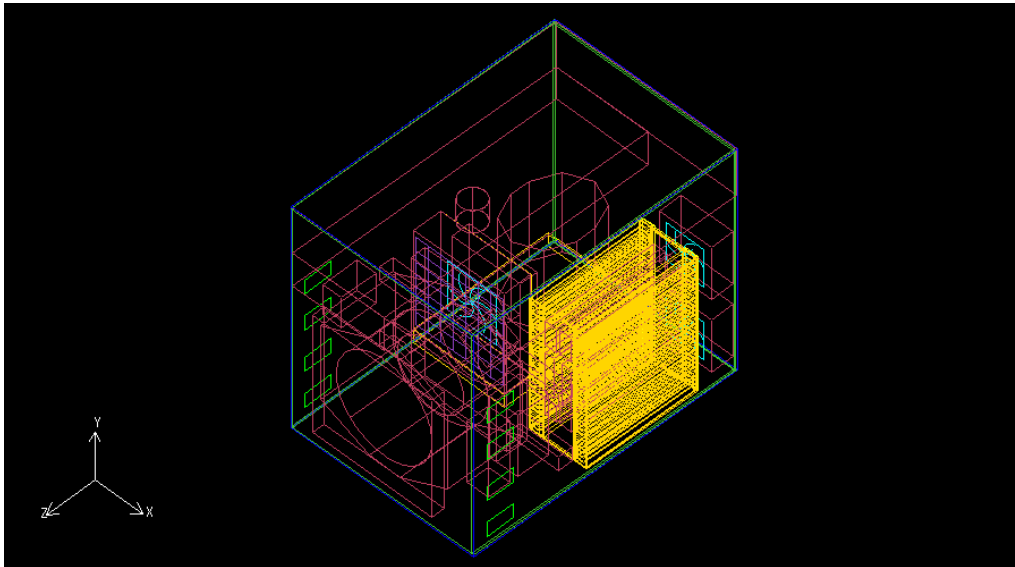


Figure 3.1-1 ICEPAK Flow Model of HRF Refrigerated Centrifuge

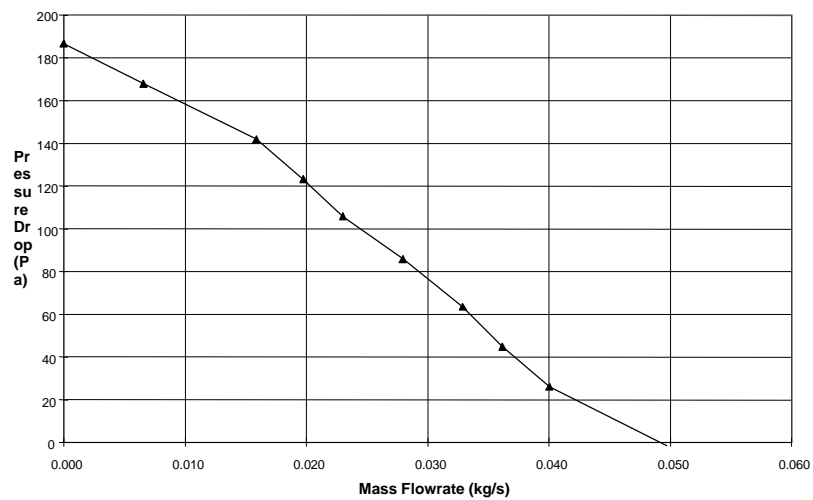


Figure 3.1-2: The Characteristic Fan Curve of the External Cooling Fan

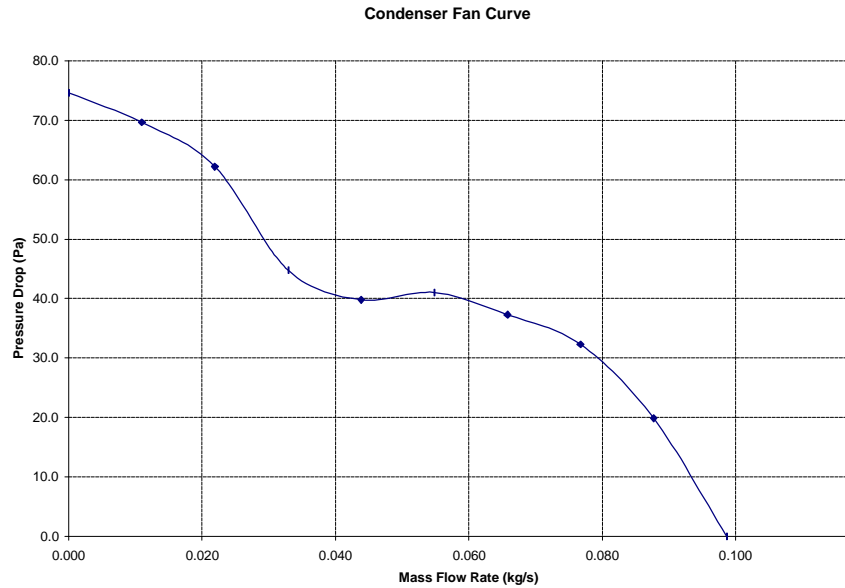


Figure 3.1-3: The Characteristic Curve For The Condenser Fan

3.2 Theory and Description of SINDA Model

SINDA is a general-purpose thermal analysis package that can solve lumped parameter representations of heat transfer problems. A conductor-capacitor (G-C) network representation is used to model the different modes of heat transfer. The problem domain is represented as discrete nodes. The SINDA package solves for the temperature at these discrete nodes. The conductance between the nodes and the capacitance at the nodes are obtained as explained below:

The heat flow rate through a conductor is given by

$$\begin{aligned}\dot{Q} &= G(T_i - T_j) \text{ For conduction, convection and mass transfer} \\ &= G(T_i^4 - T_j^4) \text{ For radiation}\end{aligned}$$

Where:

\dot{Q} = Heat Transfer Rate
 T = Absolute Temperature
 G = Conductance

Conductance:

For heat transfer by conduction, the conductance G is computed as:

$$G = KA/L$$

Where:

K = Thermal conductivity of the material
 A = Cross sectional area of the conduction path
 L = Length of conduction path

For heat transfer by convection, the conductance G is computed as:

$$G = hA$$

Where:

h = Convection coefficient
 A = Surface area

For heat transfer by mass flow, the conductance G is computed as:

$$G = \dot{m}C_p$$

where:

\dot{m} = Mass flow rate
 C_p = Specific heat Capacity

For heat transfer by radiation, the conductance G is computed as:

$$G = F\sigma A$$

where:

F = Gray Body Factor
 σ = Stefan Boltzmann Constant
 A = Surface Area

Capacitance

The thermal capacitance is computed as:

$$C = mC_p$$

where:

C = Capacitance

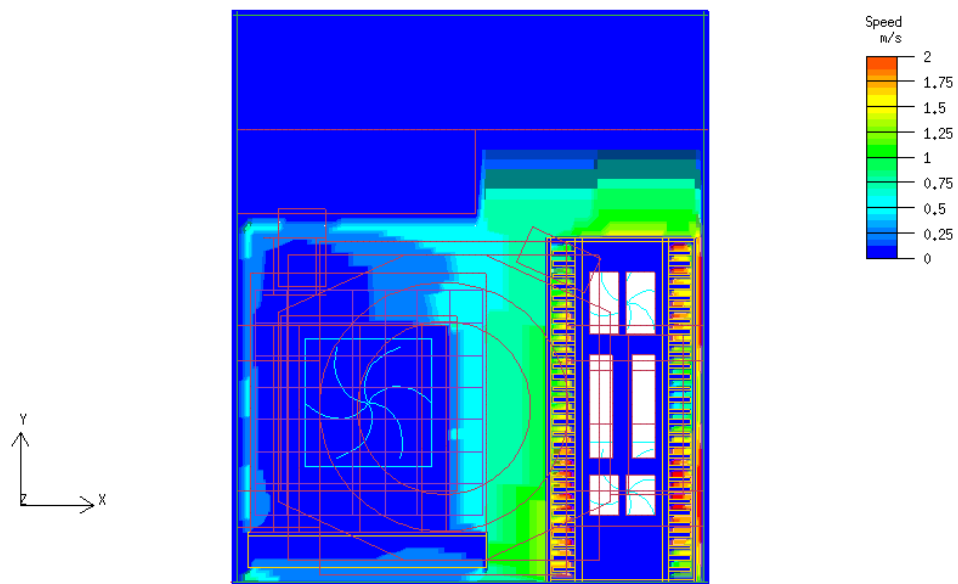
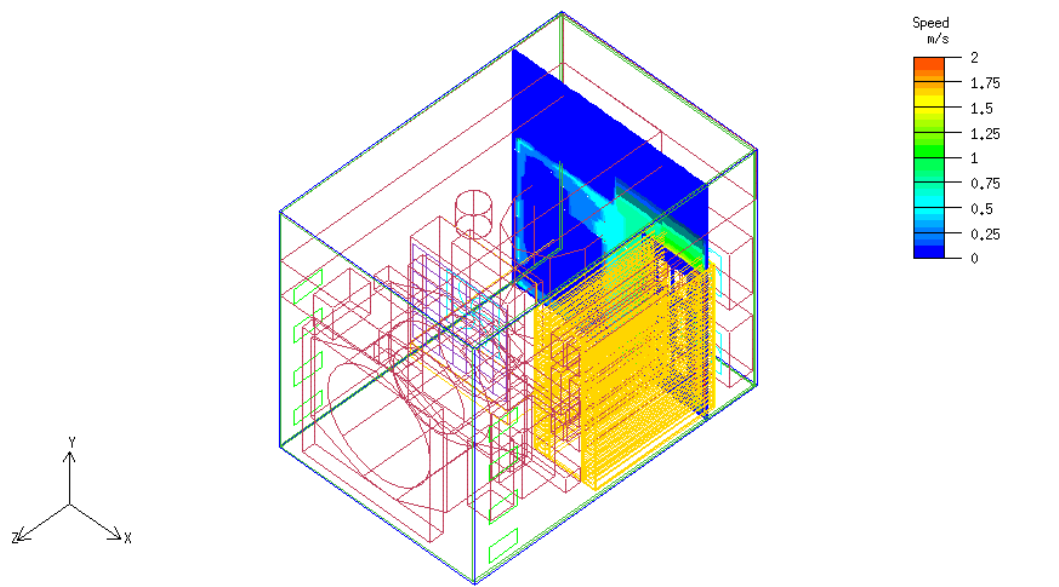
C_p = Specific heat capacity of the material

m = mass

The SINDA model was developed using nodes to represent the different components. The model was at first correlated with the test data from the prototype. The temperature characteristics of compressor and the inner door temperature were used to develop the model.

4 FLOW RESULTS

The steady state flow solution is obtained by solving the Navier Stokes equations. The flow solution is obtained in terms of velocity and pressure at discrete points. Flow model was developed and solved using ICEPAK software package. The flow distribution inside the unit and the flow rate through the unit were predicted. The total flow rate through the external cooling fans is 133 cfm. The flow rate through the condenser fan is 72 cfm. The speed contours at a section through the compressor and PCSM are shown in Figure 4.1



5 THERMAL RESULTS

The results for the following cases are discussed in this Section:

- Case1) Nominal operation with a cabin air temperature of 28C
- Case2) Nominal operation with a cabin air temperature of 20 C
- Case3) Failure of both external cooling fans
- Case4) Failure of one external cooling fan assuming the same duty cycle after fan failure
- Case5) Failure of one external cooling fan assuming continuous refrigeration loop after fan failure

The refrigeration duty cycle shown in Table 1-1 of Section 1 was used in all the cases before fan failure. The analysis was run for 60 minutes and the duty cycle was extended beyond 30 minutes of operation, by considering the refrigeration loop to be on for 2.3 minutes and then off for 1.5 minutes in cases 1, 2 and 4. The refrigeration loop was considered to be on continuously after fan failure for cases 3 and 5.

5.1 Case 1) Nominal Operation With a Cabin Temperature of 28C

The results for the case of Nominal operation are plotted in Figures 5.1.1 to 5.1.6. The touch temperature plot shown in Figure 5.1.1 indicates that there will be no touch temperature violation. It can be seen that the lowest temperature on the door is above the condensation dew point limit of 15.6 C and hence there will be no condensation on the front panel. The operational time of the Refrigerated Centrifuge is 30 minutes. So the temperatures of components at 30 minutes after the unit starts is shown in Table 5.1-1

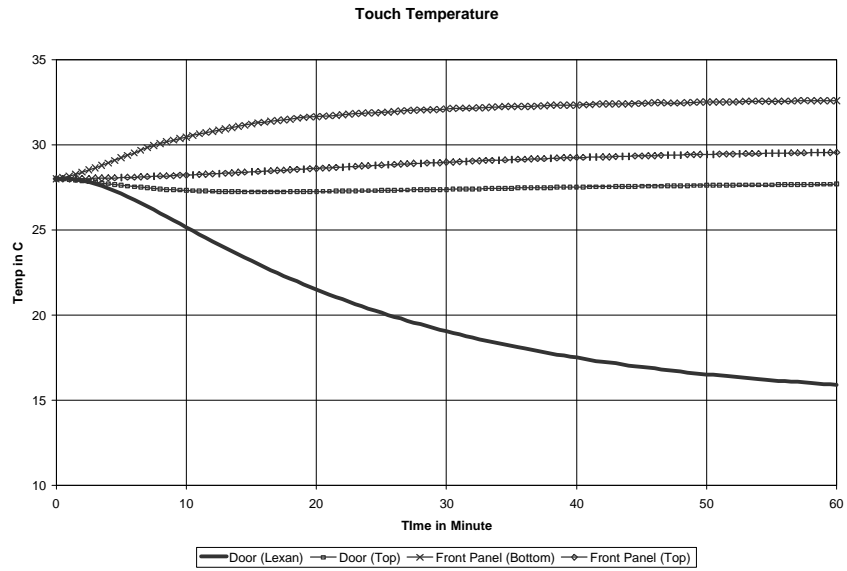


Figure 5.1.1 Touch Temperature History for Case1 (Nominal Operation With a Cabin Air Temperature of 28C)

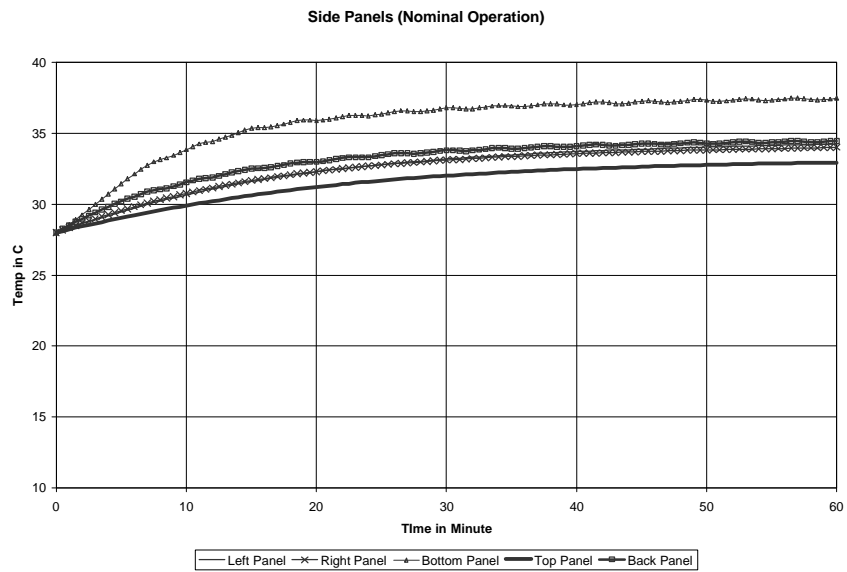


Figure 5.1.2 Temperature History of Side Panels Case1 (Nominal Operation With a Cabin Air Temperature of 28C)

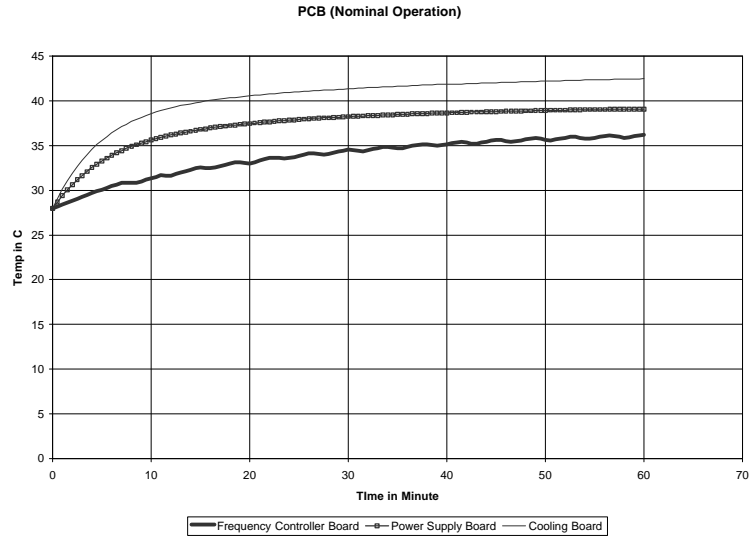


Figure 5.1.3 Temperature History of PCBs Case1 (Nominal Operation With a Cabin Air Temperature of 28C)

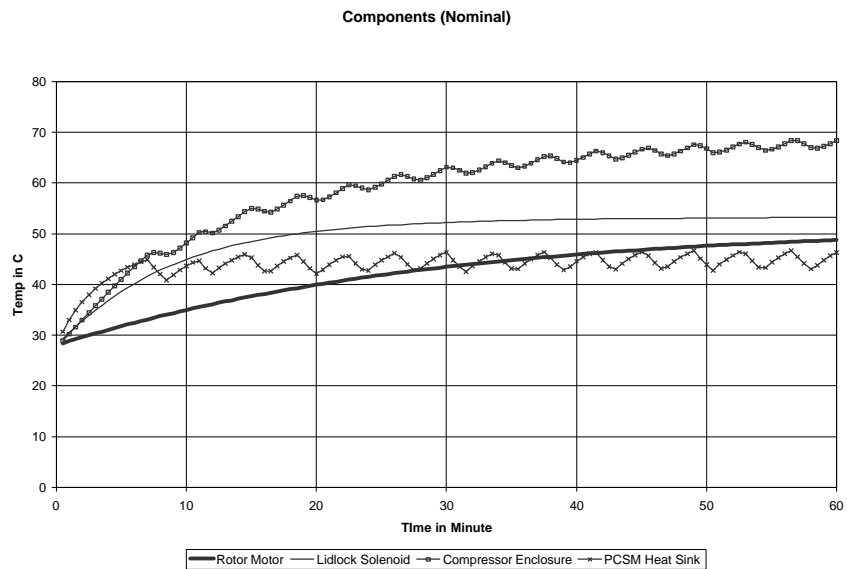


Figure 5.1.4 Temperature History of RC Components Case1 (Nominal Operation With a Cabin Air Temperature of 28C)

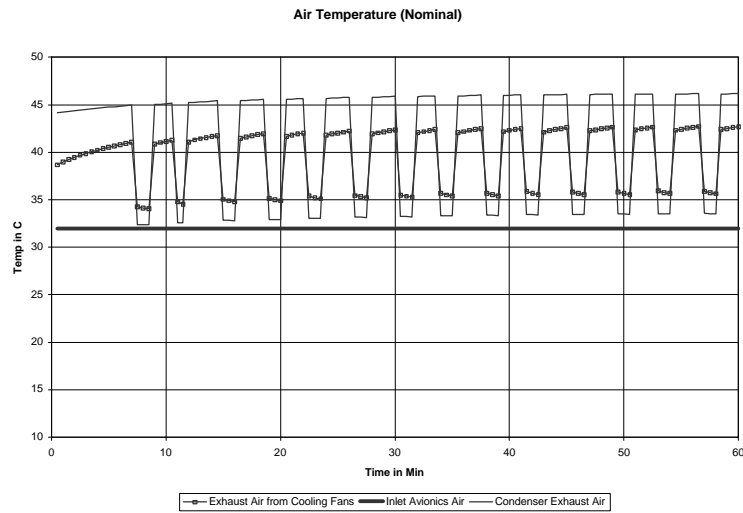


Figure 5.1.5 Air Temperature History Case1 (Nominal Operation With a Cabin Air Temperature of 28C)

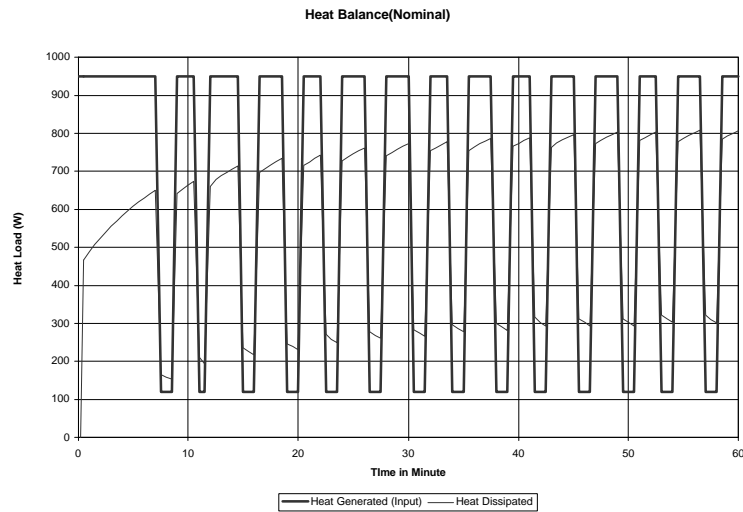


Figure 5.1.6 Heat Balance Plot Case1 (Nominal Operation With a Cabin Air Temperature of 28C)

(Case 1 Nominal Operation)	
Components/Air/Panels	Temperature at 30 minutes (In C)
<u>Touch Temperatures</u>	
Door (Lexan)	19
Door (Top)	27.5
Front Panel (Top)	30.8
Front Panel (Bottom)	32.1
<u>Air</u>	
Condenser Exhaust	45.9
Cooling Fans	42.4
<u>Components</u>	
Frequency Controller Board	34.6
Power Supply Board	38.2
Cooling Board	41.4
Compressor Enclosure	63.1
PCSM Heat Sink	46.4
Rotor Motor	43.4
Lidlock Solenoid	52.2
<u>Side Panels</u>	
Left Panel	33.2
Right Panel	33.1
Bottom	36.8
Top Panel	32.0
Back Panel	33.8

Table 5.1-1 Temperatures of Components and Air After 30 Minutes of Operation
For Case1 (Nominal Operation With A Cabin Air Temperature of 28C)

5.2 Case 2) Nominal Operation With a Cabin Air Temperature of 20 C

The analysis was run to check the lowest temperature on the door, when the cabin temperature drops to 20 C. The temperature on the lexan part of the door is plotted in Figure 5.2.1. It was observed that the lowest temperature dropped below 15.6 C indicating the possibility of condensation. So the model was re-run to find out the effective conductivity required in this region of door that would avoid condensation. It was determined that the effective conductivity in this region has to be decreased to 35 percent of the original Lexan conductivity to avoid condensation for one hour of operation, and the temperature history of this door is also shown in the same figure. It can be observed that the lowest temperature on this door stays above 15.6 C, thus eliminating the possibility of condensation. For the Flight Unit, the design of the door has been changed to reduce the effective conductivity by introducing an air gap. This will increase the lowest temperature on the front door and depending on the effective insulation that the air gap provides, condensation could be eliminated on the Flight Unit door and improve the thermal efficiency of the unit/

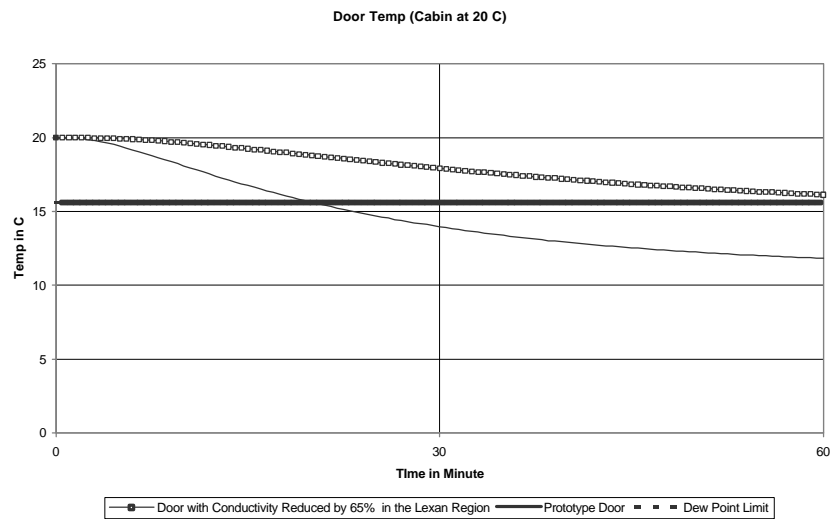


Figure 5.2.1 Temperature History of Lexan Part of Door for Case2 (Nominal Operation With a Cabin Air Temperature of 20C)

5.3 Case3) Failure of Both External Cooling Fans

This case is considered to predict the temperature distribution of components in the event of failure of both cooling fans. It is assumed that the fans fail 15 minutes after the start of the unit. A thermal switch is located on the compressor. It turns off power to the refrigeration loop when the temperature reaches 105 C. The power is turned on again when it reaches 61 C. The analysis is run for one hour to check how long it will take for the temperature on the surface of compressor to reach the thermal switch limit of 105C.

In this case, condenser fan is assumed to be running. The flow rate through this fan is 70 cfm. It is assumed that 25% of this flow rate is being drawn through the vents and discharged through the fan openings. Also it is assumed that the refrigeration loop and the compressor will run continuously after failure of the fans

The results are shown in Figures 5.3.1 to 5.3.6. The touch temperature limits are not violated as shown in Figure 5.3.1. As seen in the nominal case, the lowest temperature on the door also remains above the dew point limit of 15.6 C.

It can be seen that the temperature on the compressor reaches 105 C in about 22.5 minutes after fan failure. The power to the refrigeration loop is turned off at this time. The temperatures of components and air reached at this time are shown in Table 5.3-1. The temperatures reached at 30 minutes after the start of the unit are also shown in the same table.

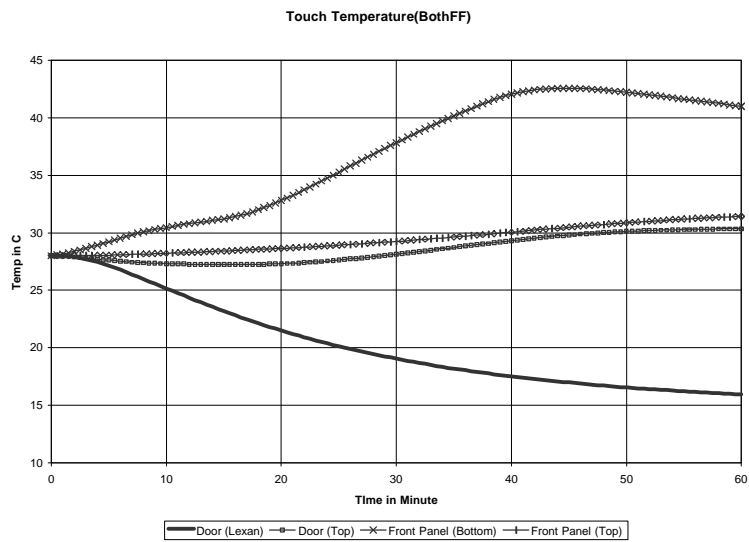


Figure 5.3.1 Touch Temperature History for Case3 (Failure of Both External Cooling Fans)

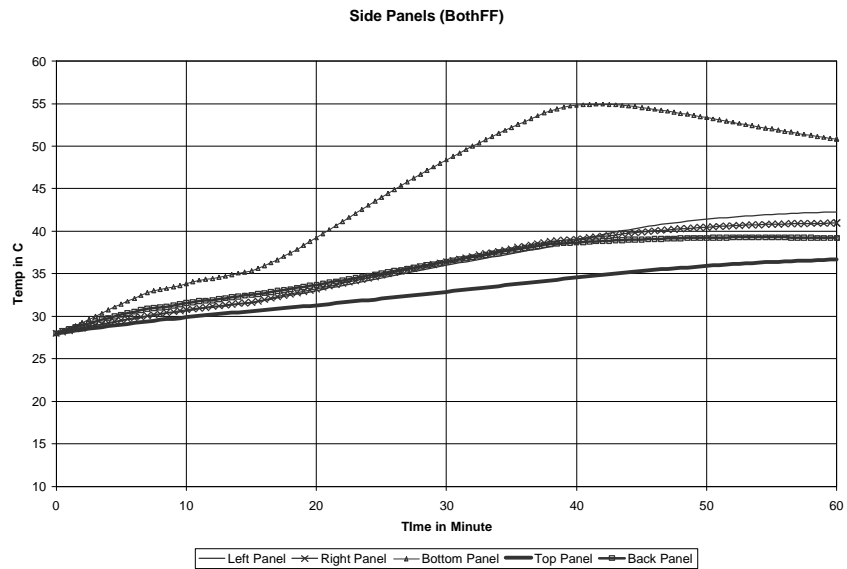


Figure 5.3.2 Temperature History of Side Panels for Case3 (Failure of Both External Cooling Fans)

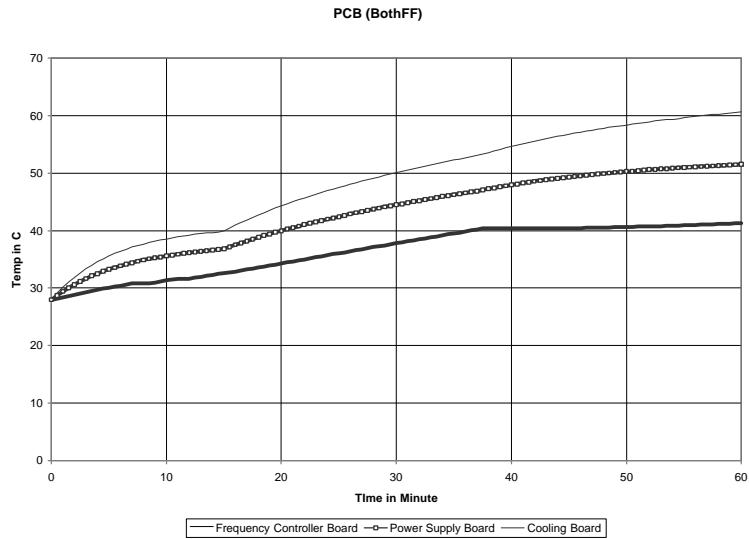


Figure 5.3.3 Temperature History of PCBs for Case3 (Failure of Both External Cooling Fans)

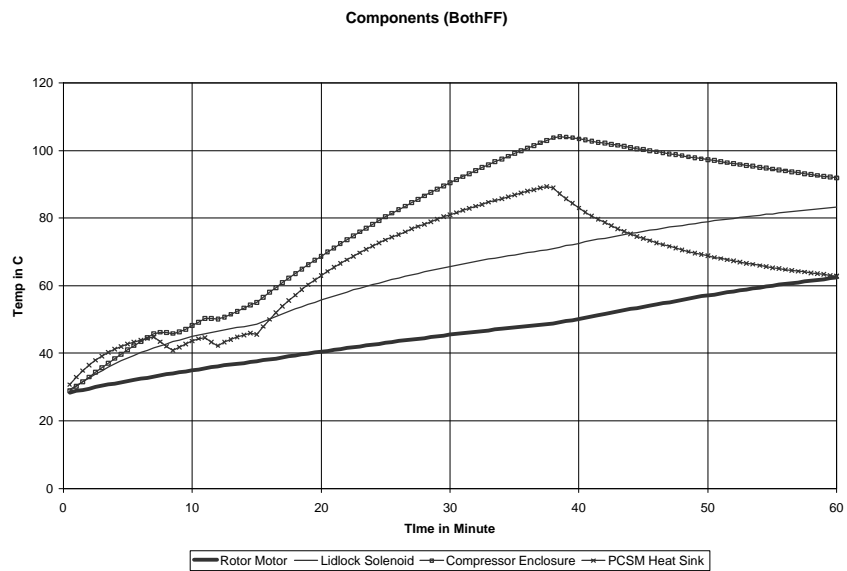


Figure 5.3.4 Temperature History of RC Components for Case3 (Failure of Both External Cooling Fans)

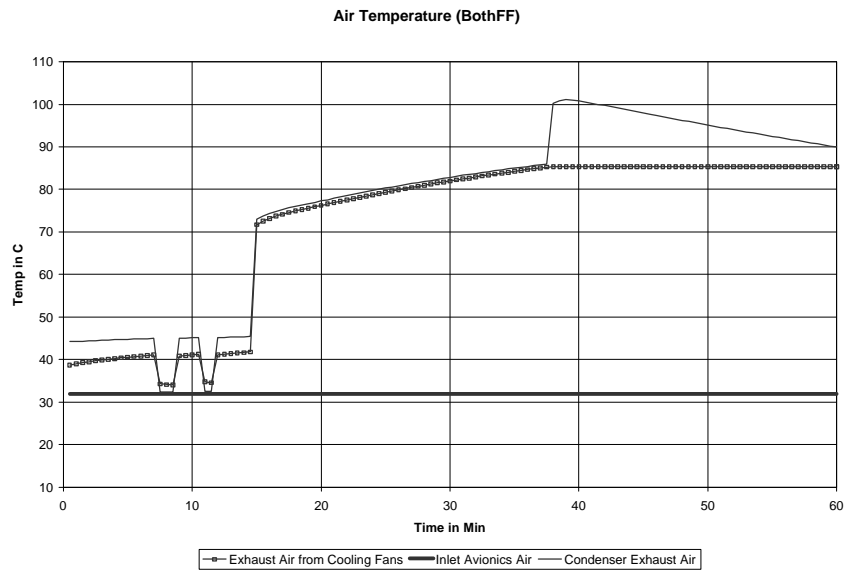


Figure 5.3.5 Air Temperature History for Case3 (Failure of Both External Cooling Fans)

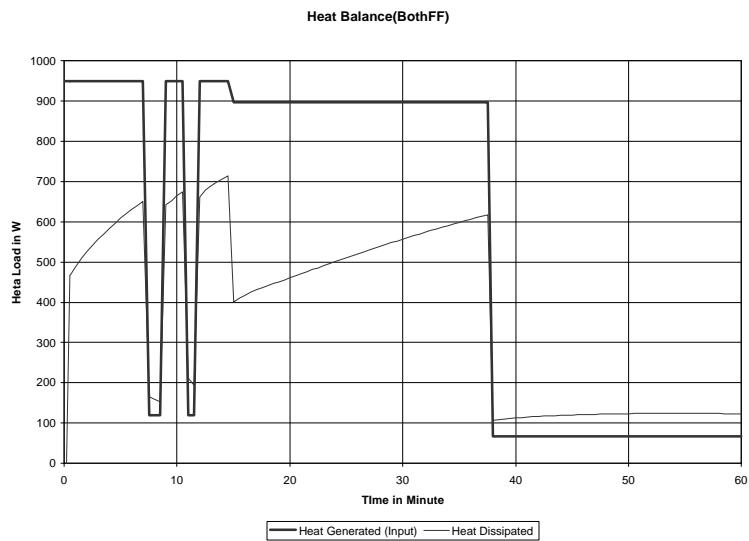


Figure 5.3.6 Heat Balance Plot for Case3 (Failure of Both External Cooling Fans)

(Case 3 Failure of Both Cooling Fans)		
Components/Air/Panels	Temperature (C) at 30 minutes	Temperature (C) at 37.5 minutes (22.5 after fan failure)
<u>Touch Temperatures</u>		
Door (Lexan)	19	17.8
Door (Top)	28.2	29
Front Panel (Top)	32	33.3
Front Panel (Bottom)	37.9	41.2
<u>Air</u>		
Condenser Exhaust	82.8	86
Cooling Fans	82	85.3
<u>Components</u>		
Frequency Controller Board	37.8	40.4
Power Supply Board	44.5	47.1
Cooling Board	50.1	53.3
Compressor Enclosure	90.4	105
PCSM Heat Sink	81	89.4
Rotor Motor	45.5	48.6
Lidlock Solenoid	65.7	70.6
<u>Side Panels</u>		
Left Panel	36.0	38.1
Right Panel	36.4	38.7
Bottom	48.4	53.9
Top Panel	32.9	34.2
Back Panel	36.4	38.4

Table 5.3-1 Temperatures of Components and Air
for Case3 (Failure of Both External Cooling Fans)

5.4 Case4) Failure of One External Cooling Fan Assuming the Same Duty Cycle After Fan Failure

The case of failure of one of the external cooling fans is analyzed to check the temperatures of the components. It is assumed that the duty cycle of the compressor remains same. The results for this case are shown in Figures 5.4.1 to 5.4.6. It is assumed that one of the fans failed 15 minutes after the unit started. The analysis is run for 60 minutes. In this case as the refrigeration loop is turned on and off based on the duty cycle, the thermal switch limit of 105 C will not be reached during the 60 minutes of operation. It is observed that the touch temperature limits are not violated for this case. The temperatures of components and air reached at 30 minutes of operation are shown in Table 5.4-1.

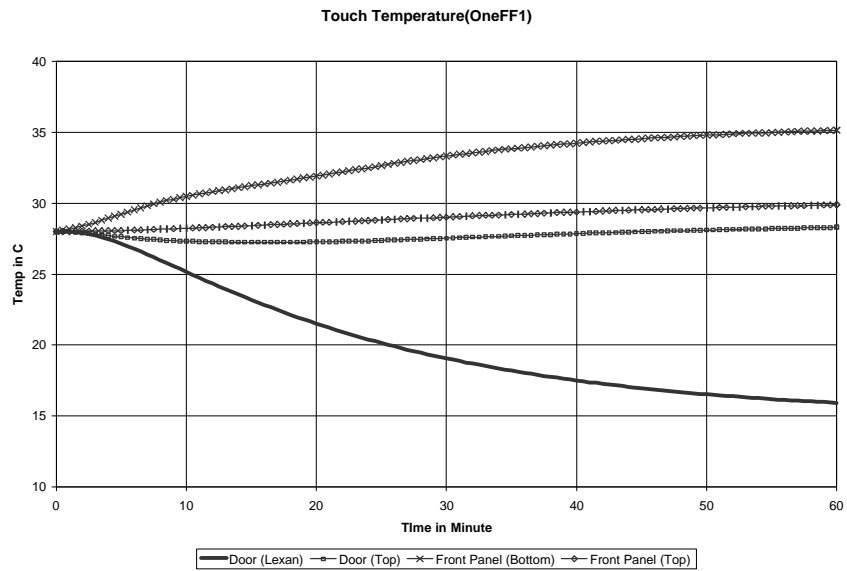


Figure 5.4.1 Touch Temperature History
for Case4 (Failure of One External Cooling Fan assuming the Same Duty Cycle)

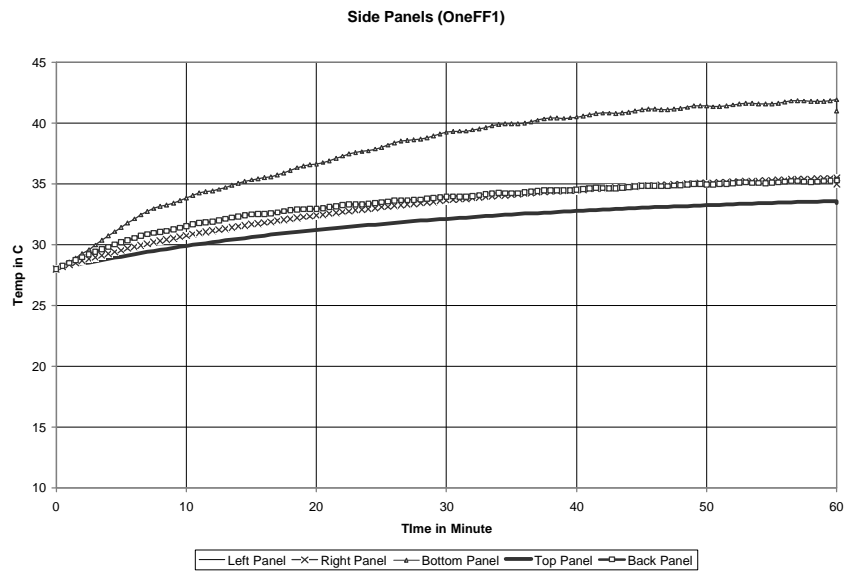


Figure 5.4.2 Temperature History of Side Panels
for Case4 (Failure of One External Cooling Fan assuming the Same Duty Cycle)

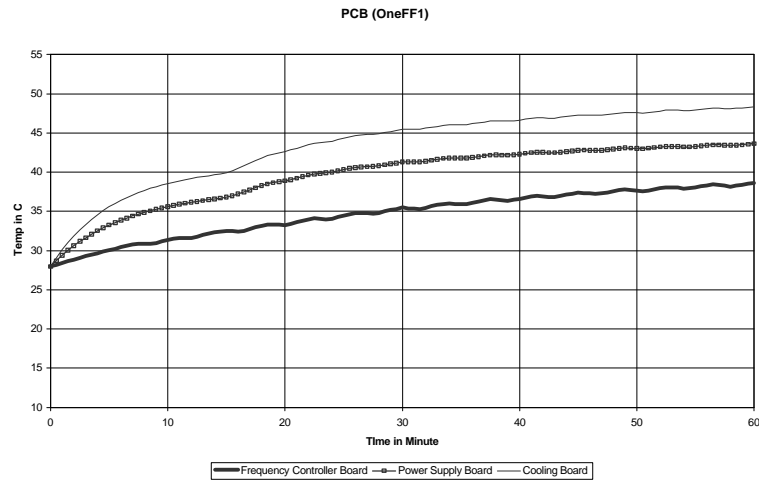


Figure 5.4.3 Temperature History of PCBs
for Case4 (Failure of One External Cooling Fan assuming the Same Duty Cycle)

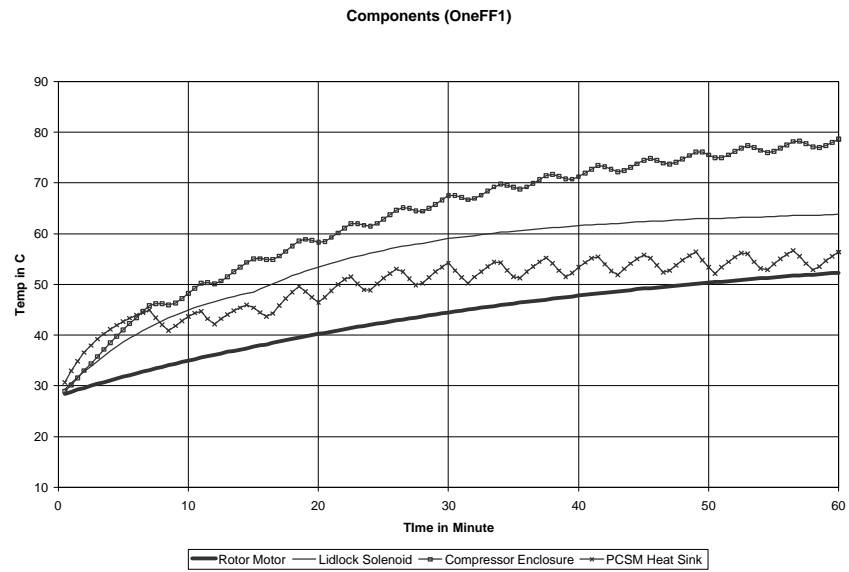


Figure 5.4.4 Temperature History of RC Components
for Case4 (Failure of One External Cooling Fan assuming the Same Duty Cycle)

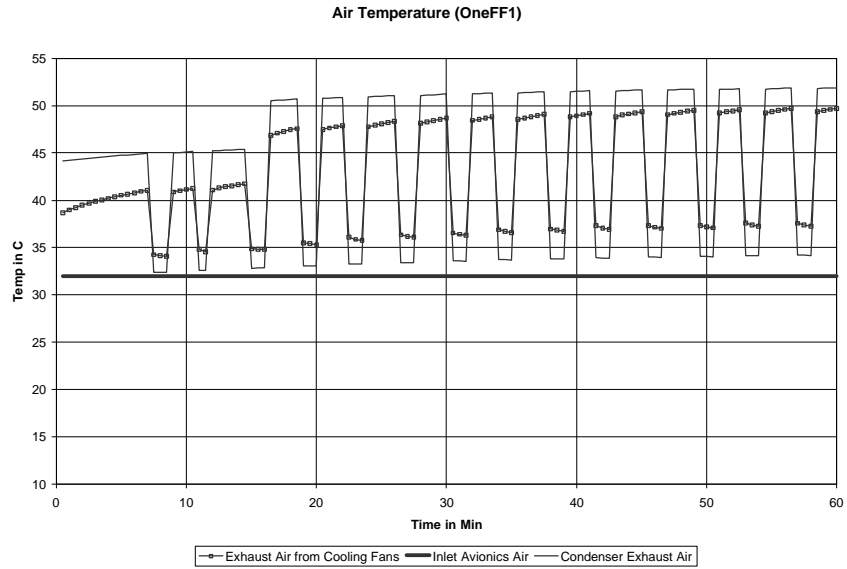


Figure 5.4.5 Air Temperature History for Case4 (Failure of One External Cooling Fan assuming the Same Duty Cycle)

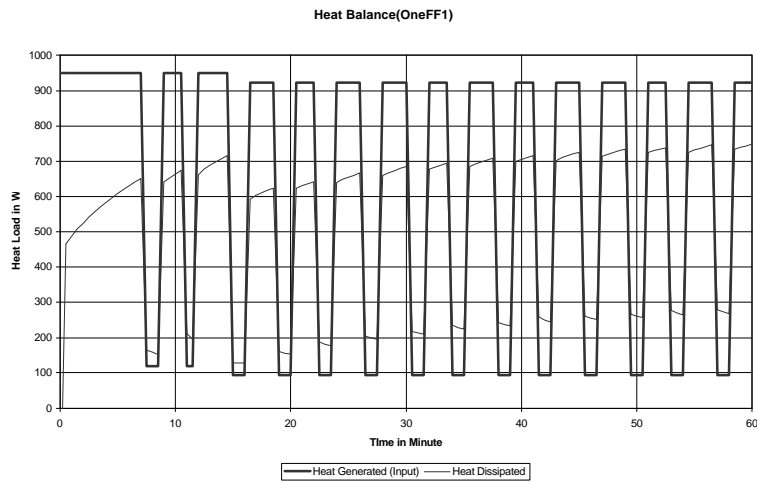


Figure 5.4.6 Heat Balance Plot for Case4 (Failure of One External Cooling Fan assuming the Same Duty Cycle)

(Case 4)	
Components/Air/Panels	Temperature at 30 minutes (In C)
<u>Touch Temperatures</u>	
Door (Lexan)	19
Door (Top)	27.5
Front Panel (Top)	31.1
Front Panel (Bottom)	33.3
<u>Air</u>	
Condenser Exhaust	51.3
Cooling Fans	48.7
<u>Components</u>	
Frequency Controller Board	35.5
Power Supply Board	41.3
Cooling Board	45.5
Compressor Enclosure	67.5
PCSM Heat Sink	54.2
Rotor Motor	44.5
Lidlock Solenoid	59
<u>Side Panels</u>	
Left Panel	33.5
Right Panel	33.7
Bottom	39.2
Top Panel	32.1
Back Panel	34.0

Table 5.4-1 Temperatures of Components and Air After 30 Minutes of Operation for Case4
(Failure of One External Cooling Fan assuming the Same Duty Cycle)

5.5 Case5) Failure of One External Cooling Fan Assuming Continuous Refrigeration Loop after Fan Failure

The case of failure of one of the external cooling fans is re-considered here by assuming that the compressor will run continuously (refrigeration loop) after fan failure. The results for this case are shown in Figures 5.5.1 to 5.5.6. It is assumed that fan fails 15 minutes after the unit starts. The analysis is run for 60 minutes. In this case, the thermal switch limit of 105 C will be reached in 43.5 minutes after fan failure. It is observed that the touch temperature limits are not violated. The temperatures of the components at 30 minutes after the start of the unit and 43.5 minutes after fan failure are shown in Tables 5.5-1.

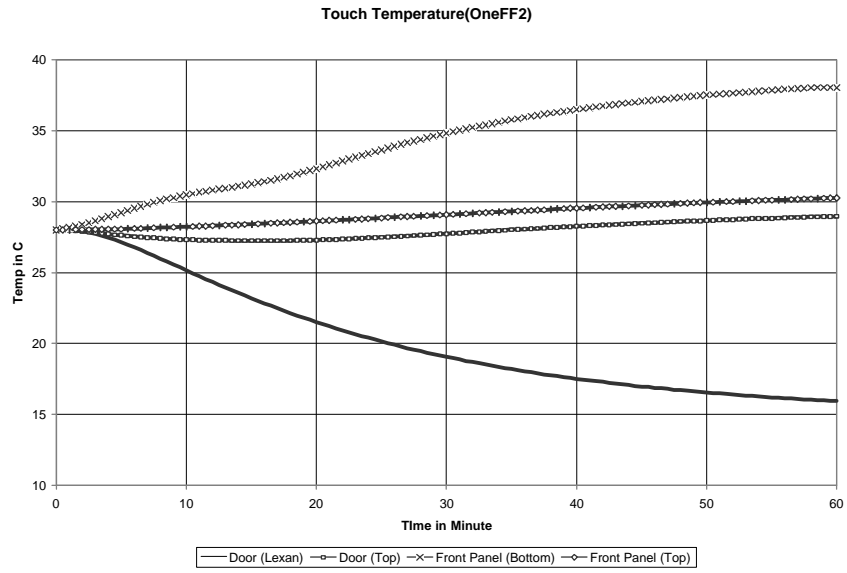


Figure 5.5.1 Touch Temperature History for Case5
(Failure of One External Cooling Fan assuming Continuous Refrigeration Loop after fan failure)

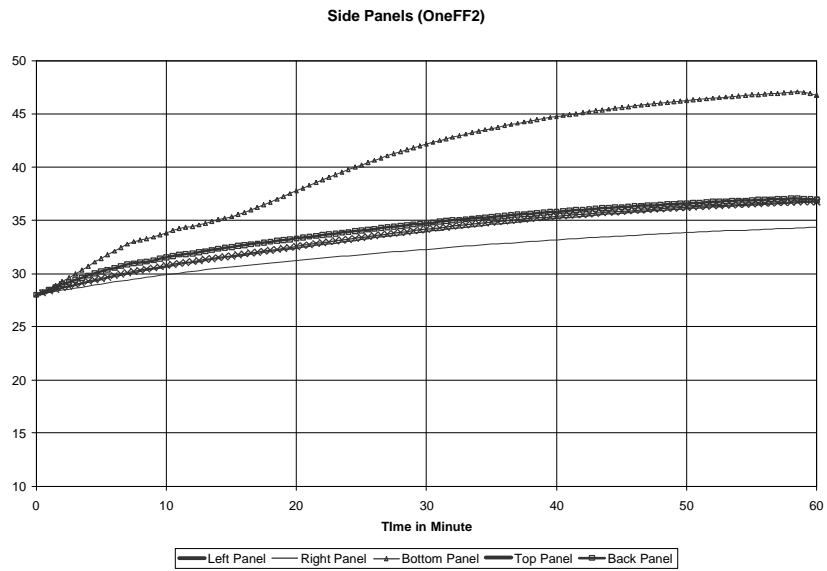


Figure 5.5.2 Temperature History of Side Panels for Case5
(Failure of One External Cooling Fan assuming Continuous Refrigeration Loop after fan failure)

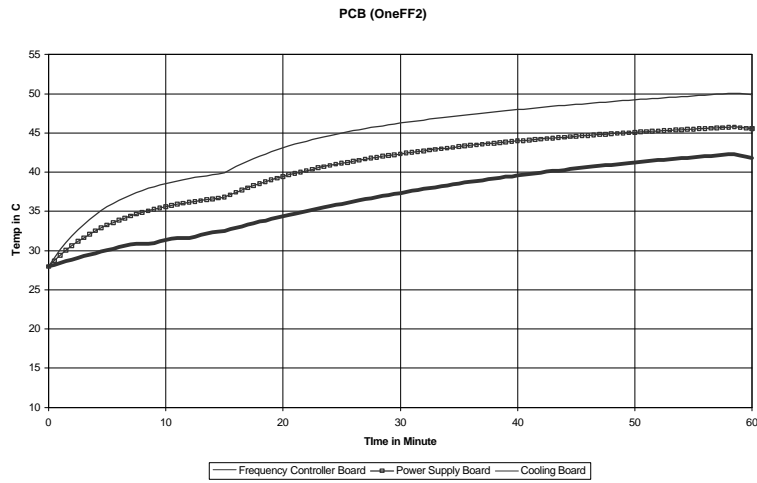


Figure 5.5.3 Temperature History of PCBs for Case5
(Failure of One External Cooling Fan assuming Continuous Refrigeration Loop after fan failure)

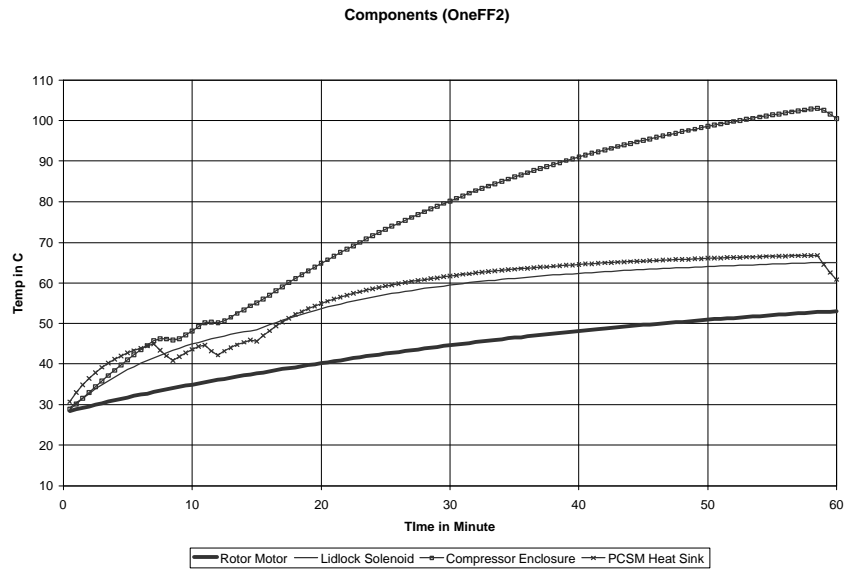


Figure 5.5.4 Temperature History of RC Components for Case5
(Failure of One External Cooling Fan assuming Continuous Refrigeration Loop after fan failure)

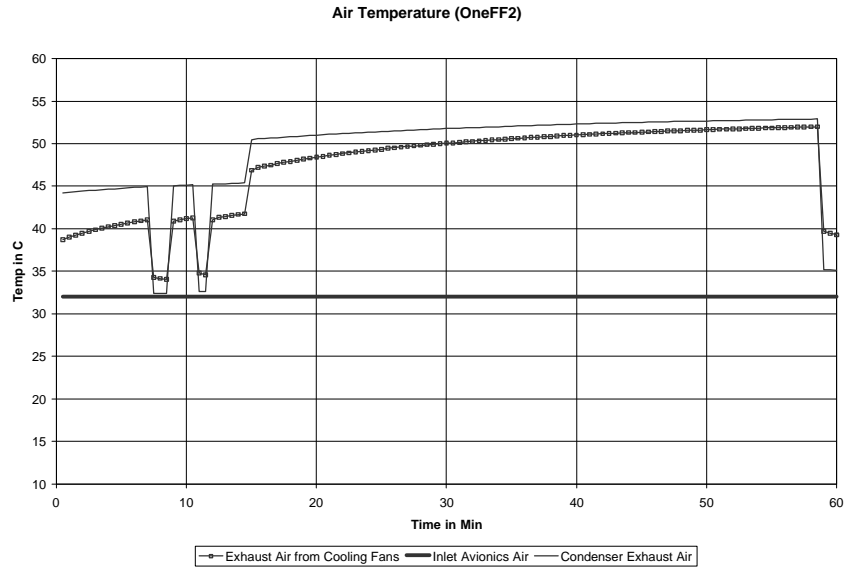


Figure 5.5.5 Air Temperature History for Case5
(Failure of One External Cooling Fan assuming Continuous Refrigeration Loop after fan failure)

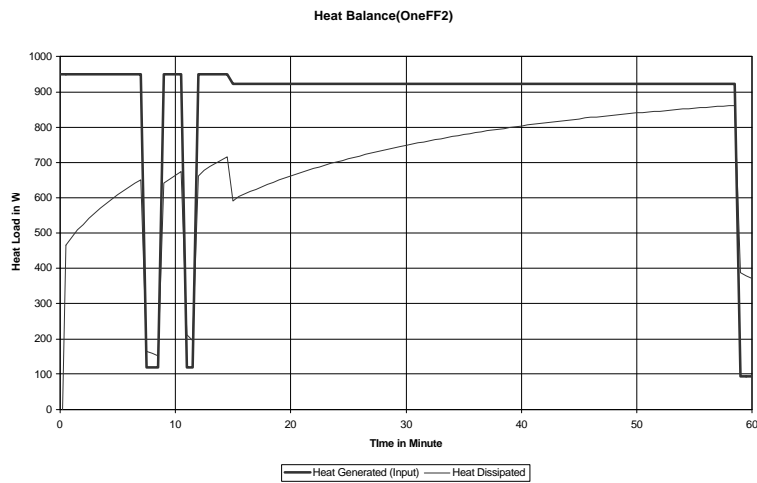


Figure 5.5.6 Heat Balance Plot for Case5
(Failure of One External Cooling Fan assuming Continuous Refrigeration Loop after fan failure)

(Case 5)		
Components/Air/Panels	Temperature at 30 minutes (In C)	Temperature (C) at 58.5 minutes (43.5 minutes after fan failure)
<u>Touch Temperatures</u>		
Door (Lexan)	19.1	16
Door (Top)	27.7	28.9
Front Panel (Top)	31.5	33.2
Front Panel (Bottom)	34.8	38.1
<u>Air</u>		
Condenser Exhaust	51.8	52.9
Cooling Fan	50	52
<u>Components</u>		
Frequency Controller Board	37.4	42.3
Power Supply Board	42.3	45.8
Cooling Board	46.3	50.1
Compressor Enclosure	80.3	105
PCSM Heat Sink	61.7	66.8
Rotor Motor	44.6	52.8
Lidlock Solenoid	59.5	65
<u>Side Panels</u>		
Left Panel	34.0	36.7
Right Panel	34.2	36.7
Bottom	42.2	47.1
Top Panel	32.3	34.3
Back Panel	34.7	37.1

Table 5.5-1 Temperatures of Components and Air for Case5
(Failure of One External Cooling Fan assuming Continuous Refrigeration Loop after fan failure)

6 CONCLUSIONS

The temperature profiles of the components, front and side panels, and air flowing inside the unit are predicted for cases of nominal and fan failure operations. The results are tabulated at the end of operational time of 30 minutes. However, the analysis was run for 60 minutes and the results are plotted as temperature history plots.

The results show that the maximum temperature on the front surface of the unit does not exceed the touch temperature limit of 45C during nominal or fan failure operation. The temperature on the front door was checked for possibility of condensation at lower cabin temperatures. The prototype door showed possibility of condensation if cabin air temperature drops lower than 22 C. The effective conductivity needed in this region in order to avoid condensation was evaluated. The Flight Unit door is re-designed and will have an air-gap in the Lexan region of the door. This will increase the lowest temperature on the front door and depending on the effective insulation that air gap provides, condensation could be eliminated.

The fan failure cases were analyzed by considering the failure of fans at fifteen minutes after the start of the unit. The temperatures reached at the time when the thermal switch on the compressor turns off power to the refrigeration loop are tabulated. The project engineer has to assess the compatibility of the components based on the thermal predictions in the report.